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Technical Survey /1284*

Optical Computing

by
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1. Introduction:

The advantage of optical computing is its parallelism. In the case of photography, every part of an object is focused by a camera lens onto a film to construct an image of the object. This image forming process constitutes the basis of optical parallel processing and optical computing is a technology that transforms the concept of optical processing into various information processing techniques. Various research has been conducted in the field of optical information processing to develop retrievable optical memories using the lens as the means to perform Fourier transformations or the holograms, but none of the methods has been put into practical use. They utilize the devices in classical optics such as the lenses to perform basically different functions from electronic devices. The information data processed by the optical devices are the analog quantities that represent focusing, transmission, reflection and phase difference and therefore are incompatible with the digital processing used in the current information processing techniques. However, recent progress in optical

* Numbers in margins indicate foreign pagination.

technologies such as the development of spatial light modulators and optical semiconductor devices have not only made microscopic control of light possible, but also made the optical technologies compatible with electronics. This fusion of optics and electronics has opened a new avenue of opportunities for future information processing technologies. The advancement in optical switching techniques has also contributed to the improvement in the degree of freedom of optical digital processing. The parallel computing method that expresses digital quantities in the form of patterns and performs digital processing as a part of pattern processing has also been tried. These attempts may overturn the common belief that optical technologies are basically incompatible with digital processing. One of the hot topics in the field of optical computing is the application of optical technologies to neural networks for the purpose of developing new information processing capabilities such as learning and recalling memories by studying animals' information processing systems. Optical technologies are expected to play a significant role in the development of neural networks that require a great number of line connections. The reason why optical technologies are in demand in parallel digital optical computing and optical neurotechnology is that light is not only flexible and capable in handling a large volume of information, but also has excellent connectability. Optical interconnection is a term used to represent a branch of optical technology that is intended to realize the high density optical network systems within a short distance. In this paper, the most recent progress in optical computing methods such as the parallel optical digital computing and neural computing will be reviewed.

2. Parallel optical digital computing:

Parallel optical digital computing system that is based on the principle of logic computing makes use of the parallelism of light and is designed to process the data obtained from a source with more than one dimension such as a picture. The system, like electronic calculators, consists of three components that are logic gate, logic circuit and computing system.

2.1 Optical logic gate:

There are two types of logic gates. One of them conducts logic processing in temporal domain using nonlinear optical elements and digitize the intensity, phase and polarization of light by means of switches. The roles of spatial light modulator (SLM) are not only to accelerate the speed of the device, but also to collect the data two-dimensionally and perform parallel processing of the data.

At present, most of SLMs are of the dielectric-type /1285
SLMs such as liquid crystals and PROMs (Pockels readout optical modulators), but semiconductor-type SLMs have also been developed. SEEDs (self electrooptic effect devices) developed at the AT&T Bell Research Laboratory utilize the changes in absorption and reflection rates of light that take place upon the application of voltage to semiconductors with multiple quantum wells. They are the most well developed devices for optical computing. S-SEED combines two SEEDs [1], (Fig.1) and L-SEED for logic computing are a few examples of derivatives that have been expanded from the original SEED.

On the other hand, the development of surface light emitting devices has been in progress and two-dimensional optoelectronic devices that not only combine the function of pnpn-type thyristors with those of light emitters and receivers, but also come with switching and memory functions [2] have been devised.

Another optical gating method is the digital method that utilizes spatial coding, a unique feature of optical techniques. For example, the information data are coded with 1 and 0 for black and white or 0 and 1 for white and black as shown in Fig.2 and the coded data are processed optically parallel as a block to achieve large scale processing. Various methods have been proposed with regard to this technique such as inter neighboring image elements logic [3], code substitution logic [4], cellular logic [5] and BIA (binary image algebra) [6].

These methods can be used in coding and processing the information utilizing the spatial parallelism of light, but they can perform only verifications by classical optic systems at present. Therefore their future is dependent on the improvements in hardware systems such as SLM.

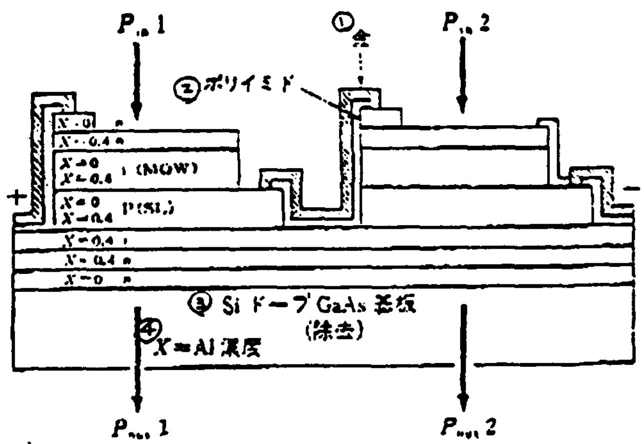

Fig.1 Structure of S-SEED [1]

[Key]
1. Gold
2. Polyimid
3. Si doped GaAs base plate (to be removed)
4. X= Al density

2.2 Optical logic circuit:

Optical logic circuits are composed of a combination of logic gates and therefore various logic circuits can be made

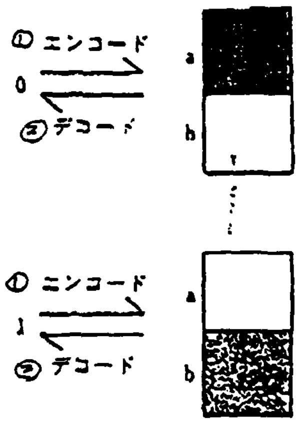

Fig.2 Example of spatial coding
[Key] 1. Encoding
2. Decoding

by changing the connection between logic gates. Optical connections may be divided into two categories -namely, the space invariant method in which connection mode is same for all kinds of data and the space variant method in which different connection modes are used. The former utilizes a command to process a large volume of information data called SIMD (single instruction multi-data stream) while the latter uses multiple number of commands called MIMD (multi-instruction multi-data stream).

2.3 Parallel computing system:

The architecture of a parallel digital optical computing system is dependent on the structure of the optical logic circuit and various architectures have been proposed. However, no working system has been developed and efforts are being made to evaluate basic blocks. AT&T has been investigating the feasibility of ultra high speed parallel pipe-line processors using various space invariant optical connections around SEED as well as conducting experiments on optical switching networks such as the perfect shuffle and the crossover networks [7].

It appears that AT&T has been trying to develop a general purpose parallel digital optical computer using the results of tests and at the same time devise the optical switches that can be applied to optical communication networks.

As for the computing systems based on the pattern /1286 coding logic, a space variant connection system has been proposed by the University of Southern California [6]. This system may be called free connection type non-Neumann computer and the design of its processor and the testing of its optical systems have already been launched.

OPALS (optical parallel array logic system) is a general purpose parallel digital computing system proposed by Osaka University [3]. It performs the logic processing of image data and parallel numerical computing by combining the array logic, the unit of which is the basic computing module. Its success depends on hardware support.

3. Optical neurocomputing:

Optical neurocomputing is designed to realize technically the capability of animals to learn and judge by building a network that can simulate the neural networks of animals. A neural network consists of many nonlinear elements called neurons and the memory units that memorize the distribution of analog quantities called synopses that connect the neurons.

The system requires a great number of connections among the neurons and this is where optical technologies can play a significant role. Among the neural models are hopfield and backpropagation models. In either case, the converging process to the stable state at the lowest energy level corresponds to learning or recollection.

As for computing, the combination of computing that calculates the product of output power of a neuron and the synopsis load and computing that adds up the input power of each neuron is required. To perform this product-addition computing, special optical devices such as light emitting element array, SLM and light receiving element array have been developed [8].

Using optical disks that have a huge memory capacity, experiments have been conducted to develop a retrievable memory systems by recording the holograms on disks and using the coherent optical correlators [9]. Learning is also possible in the system, if retrievable optical disks are used. Though three dimensional holograms and phase conjugation performed by crystals have been used to develop the retrievable memory, a lot of improvements are required in the areas of memory capacity, response speed and SN ratio.

The uniqueness of the neural system is that the performance of the system as a whole will not be affected, even if the characteristics of each element are slightly different. **This is the advantage of neural computing that simulates biological information processing.** Optical neurocomputers are designed to recreate the information processing capabilities of human eyes such as learning and recognition of image data and the extraction of some of their features by means of electronic computers. In addition, they will probably be built in the near future /1287
with a system like the automatic translation system that performs highly advanced processing such as reasoning.

4. Optical interconnection and computer technology:

It is believed that the performance of future super computers will depend not only on the switching speed of the gate, but also on the data transmission speed between the gates. As the increase in data transmission speed cannot be achieved electronically, the idea of optical interconnection has been conceived to utilize the superior capability of optical communication. As it is compatible with the electronic computer technology, should the information

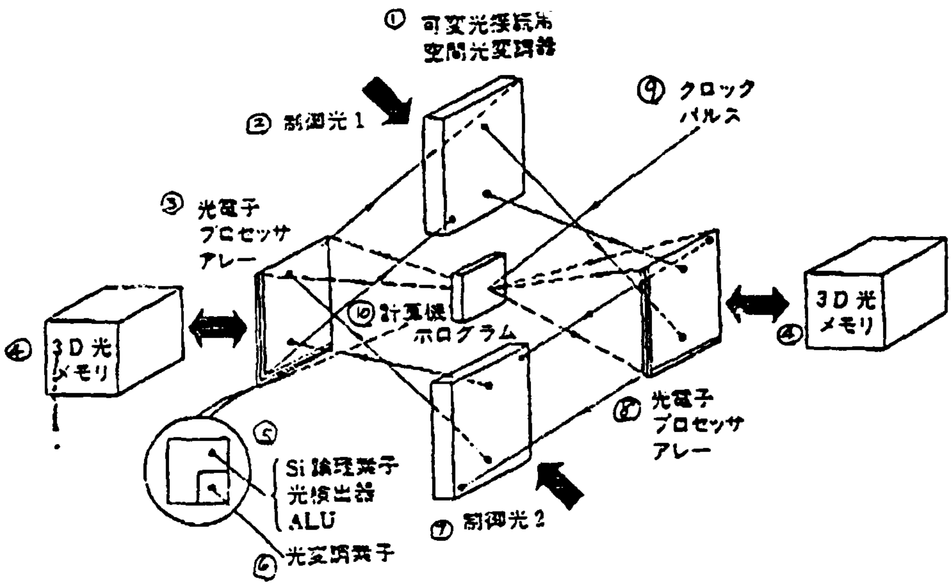

Fig.3 POEM System [10]

[Key]
1. Spatial light modulator for variable light connector
2. Controlled light 1
3. Optoelectronic processor
4. 3 D memory
5. Si logic element
   light detector
   ALU
6. Optical modulator element
7. Controlled light 2
8. Optoelectronic processor array
9. Clock pulse
10. Computer generated hologram

processing role be given to electronics and the transmission role to optics, the fusion of optical and electronic technologies is expected to occur in the near future.

Fig. 3 shows the structure of an optoelectronic information processing system called POEM (programmable opto-electronic multiprocessor) [10]. It is designed to interconnect the processors on the wafer scale LSI by light modulation and a computer generated hologram. It has been demonstrated by the computer simulations that optical connection of processors is superior to electronic connections, should their number exceed a certain limit, though it also depends on the conditions imposed by the hardware.

In this connection, the development of hardware that utilize LSI and the optical modulators made of conducting thin films has been investigated.

5. Conclusion:

This paper summarizes the present status of optical computing. Table 1 shows the relationship between parallel computer processing and optical technologies. In contrast to the conventional Neumann computer that is based on successive logic computing, new information processing is capable of performing flexible computing such as super parallel computing and neurocomputing. As optical computing utilizes the parallelism of light in space and wavelength domains and the space propagation of light, it makes flexible connections possible in contrast with electronic technology that is based on successive processing and fixed wire connections. Therefore, optical computing is a new information processing medium that meets our future needs. Though there are hardware back-ups in the case of electronic computers such as LSI, the hardware required in optical computers should be developed in the near future. For this reason, the future of optical computing depends on the advances in hardware technology.

Table 1 Relationship between parallel computing and optical technology

	① ニューロ演算	② 汎用超並列演算	
③ 演算形態	⑤ 相関、学習	⑦ 論理・記号処理	
④ 電算機の要請	⑥ 通信ネック	⑧ 逐次処理の限界	

⑨ 光技術からのアプローチ	⑩ インタコネクション	⑪ 超並列演算	
		⑫ アナログ	⑬ ディジタル
⑭ 時間域	⑮ 時間多重・超高速	⑯ 線型処理	⑰ 非線型処理
⑱ 空間域	空間多重(並列) 空間伝搬 導波制御 ⑲	⑳ 波面制御	㉑ 空間符号化
㉒ 波長域	波長多重(並列) ㉓	㉔ 波長制御	㉕ 波長符号化

[Key] 1. Neurocomputing
2. General purpose super parallel computing
3. Computing type
4. Demands for electronic computer
5. Correlation,learning
6. Communication neck
7. Logic code processing
8. Limit in successive processing
9. Optical approach
10. Interconnection
11. Super parallel computing
12. Analogue
13. Digital
14. Temporal domain
15. Temporally multiplexed, super high speed
16. Linear processing
17. Nonlinear processing

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